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(54) Imaging apparatus and method using nuclear magnetic resonance.

(57) An NMR imaging apparatus and method for direct Fourier imaging. This apparatus includes a static magnetic field generator (1, 10), gradient magnetic field generators (4x, 4z, 5, 6, 7, 8), high-frequency magnetic field generator (3, 12, 13), signal detecting detector (3, 14, 15) for detecting a nuclear magnetic resonance signal from a body (2) to be inspected, a computer (9) for performing an arithmetic operation for the detected signal to obtain the nuclear magnetic resonance intensity distribution in the to-be-inspeced body from measured values of the nuclear magnetic resonance intensity distribution at various points on a rectangular coordinate system in the Fourier space, and memories (17, 18) used for correction. In the imaging apparatus, that distortion of image data obtained by calculation from the detected signal which is caused by the deviation of the intensity of the static magnetic field from a predetermined value or the deviation of the intensity of a gradient magnetic field from a predetermined, linearly-varying intensity, is corrected by those measured values with respect to the above deviation of magnetic field intensity which are previously in the memory (18), and corrected image data is displayed on a display device (16).

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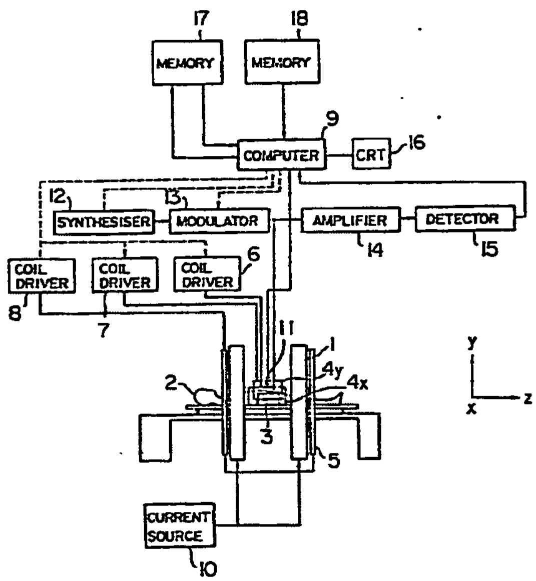
FIG.1



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MEMORY
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IMAGING APPARATUS AND METHOD USING NUCLEAR MAGNETIC RESONANCE

The present invention relates to an imaging apparatus and a method using the nuclear magnetic resonance (hereinafter simply referred to as "NMR"), and more particularly to an NMR imaging apparatus and method which can completely remove the influence of the non-uniformity of a static magnetic field and the non-linearity of a gradient magnetic field upon the image quality of an image formed by NMR imaging.

In an NMR imaging apparatus (hereinafter simply referred to as an "imaging apparatus"), the density distribution or relaxation time distribution of nuclear spin in a body to be inspected, is nondestructively detected by using the NMR phenomenon, and the cross section of a measuring target of the to-be-inspected body is reconstructed on the basis of the above distribution.

The projection-reconstruction method for forming the image of the cross section has been known. In this method, the projection of the spin density distribution or relaxation time distribution in the cross section is formed for various directions, and data thus obtained is processed to reconstruct the spin density distribution or relaxation time distribution in the cross section.

Further, another method for forming the image of the cross section, that is, the so-called direct Fourier imaging method has been known. In this method, the value

of the Fourier transform of the spin density distribution or relaxation time distribution in the cross section is directly measured at points on a Cartesian Coordinate Matrix in the Fourier space. The direct Fourier imaging method includes, for example, the Fourier zeugmatography proposed by A. Kumar et al. (refer to Journal of Magnetic Resonance Vol. 13, 1975, pages 69 to 83) and the spin warp imaging proposed by W.A. Edelstein et al. (refer to Physics in Medicine & Biology Vol. 25, 1980, pages 751 to 756).

An imaging apparatus using the direct Fourier imaging method is required to have a static magnetic field having a uniform intensity distribution in a field of view, and a gradient magnetic field superposed on the static magnetic field for giving spatial information to a signal. However, in the case where the intensity distribution of the static magnetic field is non-uniform or the intensity of the gradient magnetic field varies non-linearly, there arises a problem that a distortion is produced on the image of a cross section.

Further, the non-uniformity of the static magnetic field and the non-linearity of the gradient magnetic field produce an error in the intensity of an image signal. Accordingly, in the case where the intensity distribution of the static magnetic field is extremely non-uniform or the intensity change of the gradient magnetic field is extremely non-linear, undesirable errors in the image intensities are produced.

Incidentally, an imaging apparatus capable of

removing the infuence of the non-uniformity of a static magentic field and the non-linearity of a gradient magnetic field upon an image obtained by the projection-reconstruction method, is disclosed in a Japanese Patent Application (Application No. 23547/1983) entitled "Imaging Apparatus using Nuclear Magnetic Resonance" and filed by the present applicant.

An object of the present invention is to provide an imaging apparatus and an imaging method using the NMR which can correct the distortion of an image caused by the non-uniformity of a static magnetic field or the non-linearity of a gradient magnetic field.

Another object of the present invention is to provide an imaging apparatus and an imaging method using the NMR which can eliminate the error in the intensity of image signal caused by the non-uniformity of a static magnetic field or the non-linearity of a gradient magnetic field.

In order to attain the above objects, in an NMR imaging apparatus for direct Fourier imaging according to the present invention, the intensity distribution of a static magnetic field in a field of view and/or the intensity distribution of a gradient magnetic field in the field of view is previously measured, and an image obtained on the basis of the presence of the static and gradient magnetic fields is corrected at each of picture elements on the image, using the measured data.

Now, supplementary explanation will be made on

the above correction. In order to facilitate the explanation, the case where a two-dimensional image is formed by the Fourier zeugmatography and the distortion of the image caused by the non-uniformity of a static magnetic field is corrected, will be explained below, by way of example.

Let us denote the distribution to be imaged, the deviation of the intensity of the static magnetic field from a standard value, the intensity increment of a gradient magnetic field having an intensity gradient in an x-direction per unit distance and the intensity increment of a gradient magnetic field having an intensity gradient in a y-direction per unit distance, as $C(x, y)$, $E(x, y)$, G_x, and G_y, respectively. Then, measured data $S(t_x, t_y)$ is given by the following equation:

$$S(t_x, t_y) = \int C(x, y) \exp [-2\pi j\gamma\{(E(x, y) + (G_x x)t_x + (E(x, y) + G_y y)t_y\}] \, dxdy \qquad \ldots\ldots \quad (1)$$

where γ indicates a gyromagnetic ratio, t_x a period when the gradient magnetic field having an intensity gradient in the x-direction is applied, and t_y a period when the gradient magnetic field having an intensity gradient in the y-direction is applied. It should be noted that T_1 and T_2 relaxations are neglected in the equation (1).

Now, let us use the following integral variables:

$$\left.\begin{aligned} x' &= x + \frac{1}{G_x}E(x,\ y) \\ y' &= y + \frac{1}{G_y}E(x,\ y) \end{aligned}\right\} \quad \cdots\cdots \quad (2)$$

Then, the equation (1) can be changed to the following equation:

$$S(t_x,\ t_y) = \int C'(x',\ y')\exp[-2\pi\gamma j(G_x x' t_x + G_y y' t_y)]dx'dy' \quad \cdots\cdots \quad (3)$$

where

$$C'(x',\ y') = \frac{C(f_1(x',\ y'),\ f_2(x',\ y'))}{1 + \frac{1}{G_y}\frac{\partial E(x,\ y)}{\partial y} + \frac{1}{G_x}\frac{\partial E(x,\ y)}{\partial x}} \quad \cdots \quad (4)$$

In the equation (4), $f_1(x',y')$ and $f_2(x',y')$ indicate $X = f_1(x',y')$ and $Y = f_2(x',y')$ which are obtained by solving the equations (2).

In general, the above-mentioned gradient magnetic fields are applied so as to satisfy the following formulae:

$$G_y \gg \frac{\partial E(x,\ y)}{\partial y}, \text{ and } G_x \gg \frac{\partial E(x,\ y)}{\partial x} \quad \cdots\cdots \quad (5)$$

Accordingly, the equation (4) can be rewritten as follows:

$$C'(x',\ y') \fallingdotseq C(f_1(x',\ y'),\ f_2(x',\ y')) \quad \cdots\cdots \quad (6)$$

When two-dimensional inverse Fourier transformation is carried out for the measured data $S(t_x,\ t_y)$,

the distribution $C'(x', y')$ is obtained as is shown in eq. (3). It is clear from the formula (6) that the distribution $C'(x', y')$ is considered to be obtained by carrying out the transformation of coordinate system for the original distribution $C(x, y)$ on the basis of the equations (2). In other words, owing to the non-uniformity of the static magnetic field in a field of view, the image of a cross section is subjected to a distortion which is indicated by the equation (2).

In an ordinary imaging apparatus, a gradient magnetic field having an intensity gradient of 0.2 to 0.3 gauss/cm is used. Further, even a static magnetic field formed by the best one of magnets which are available at the present, has an intensity variation of about 3×10^{-3} percent in field of view having a diameter of 40 cm. In such a case, each of a difference $x-x'$ and a difference $y-y'$ approximately corresponds to one picture element and a half. Accordingly, a distortion on the order of two picture elements will be produced on the image of a cross section.

As mentioned previously, according to the present invention, the deviation $E(x, y)$ of the intensity of a static magnetic field from a standard value is previously measured, and the measured data thus obtained is used for correcting the image $C'(x', y')$ which is affected by the non-linearity of the static magnetic field, on the basis of the relations between coordinates (x, y) and coordinates (x', y') given by the equations (2).

Further, in the case where the intensity change of a gradient magnetic field deviates from a predetermined straight line to some extent, the deviation of the intensity of the gradient magnetic field from a linearly-varying intensity is previously measured together with the above-mentioned deviation $E(x, y)$ with respect to the static magnetic field, and the measured data thus obtained is used for correcting the image $C'(x', y')$ which is affected by the non-uniformity of the static magnetic field and the non-linearity of the gradient magnetic field.

Other features of the present invention will become apparent from the following detailed description taken in conjunction with the accompanying drawings, in which:

Fig. 1 is a block diagram showing an embodiment of an NMR imaging apparatus according to the present invention; and

Figs. 2 to 5 are waveform charts showing different pulse sequences applicable to the embodiment shown in Fig. 1.

Now, the present invention will be explained below in detail, with reference to the drawings. Fig. 1 show the outline of an embodiment of an NMR imaging apparatus according to the present invention. In Fig. 1, reference numeral 1 designates a magnet for generating a static magnetic field H_0, 2 a body to be inspected, 3 a detecting coil for generating a high-frequency magnetic field and for detecting a signal produced by the to-be-

inspected body 2, 4x coil means for generating a gradient magnetic field having an intensity gradient in the x-direction (hereinafter referred to as an "x-gradient magnetic field"), 4y coil means for generating a gradient magnetic field having an intensity gradient in the y-direction (hereinafter referred to as a "y-gradient magnetic field"), and 5 coil means for generating a gradient magnetic field having an intensity gradient in the z-direction (hereinafter referred to as a "z-gradient magnetic field"). Coil drivers 6, 7, and 8 supply currents to the coil means 4x, 4y, and 5, respectively, and each of the coil drivers 6, 7, and 8 is operated by a signal from a computer 9. The coil means 5 is formed of a pair of one-turn coils which are connected so as to be opposite in current direction to each other. The intensity of a gradient magnetic field generated by the coil means 4x, 4y, and 5 can be varied by an instruction from a device 11 for detecting the size of the to-be-inspected body 2 or from the operator of the imaging apparatus. Incidentally, reference numeral 10 designates a current source for supplying an exciting current to the magnet 1.

A high-frequency magnetic field for exciting a nuclear spin is generated in such a manner that a high-frequency signal generated by a synthesizer 12 is shaped and power-amplified by a modulator 13 and a high-frequency current is supplied from the modulator 13 to the coil 3. A signal from the to-be-inspected body 2 is received by the coil 3, and sent through an amplifier 14 to a detector

15, to be subjected to AC-DC conversion. The signal thus treated is applied to the computer 9. Image data C'(I', J') is calculated from the signal supplied to the computer 9, and stored in a memory 17. Since the image data stored in the memory 17 has a distortion, the image data C'(I', J') is corrected by data which is previously stored in a memory 18. Corrected image data C(I, J) is displayed on a CRT display 16.

First, detailed explanation will be made on an example of the correction according to the present invention, that is, the case where the image of a cross section is formed by the two-dimensional Fourier zeugmatography, and the distortion of the image caused by the non-uniformity of a static magnetic field is corrected.

Fig. 2 shows a time when each of a high-frequency pulse (namely, an RF pulse), an x-gradient magnetic field, and a y-gradient magnetic is applied to carry out the two-dimensional Fourier zuegmatography, and a time when a signal from a nuclear spin is detected. The pulse sequence shown in Fig. 2 is used for forming the image of a desired cross section parallel to the x-y plane. In Fig. 2, reference symbol RF designates an RF pulse, G_y a y-gradient magnetic field having an intensity gradient G_y, G_x an x-gradient magnetic field having an intensity gradient G_x, and NS a signal from a nuclear spin. As is apparent from Fig. 2, a 90° RF pulse is first applied to a to-be-inspected body, to tilt the nuclear spin in the body by an angle of 90°. Immediately thereafter, the Y-gradient

magnetic field is applied for a period t_y. As soon as the period t_y terminates, the X-gradient magnetic field is applied and the observation of NMR signal is started. Using the pulse sequence shown in Fig. 2, the object spin-density is measured on the rectangular coordinate points in the Fourier space. The above measurement is carried out for various values of the period t_y. A two-dimensional signal $S(t_x, t_y)$ obtained from such measurement for various values of the period t_y is related to the nuclear spin distribution in the desired cross section, as mentioned below:

$$S(t_x, t_y) = \int C(x, y)\exp\{-2\pi j\gamma(G_x x t_x + G_y y t_y)\}dxdy \quad \ldots\ldots \quad (7)$$

However, it is to be noted that the equation (7) holds only when the intensity distribution of the static magnetic field is uniform and the intensity of each of the gradient magnetic fields varies linearly in the x- or y-direction, and that a relaxation term is neglected in the equation (7). As can be seen from the equation (7), the nuclear spin distribution (x, y) in the desired cross section can be obtained by carrying out the two-dimensional inverse Fourier transformation for the two-dimensional signal $S(t_x, t_y)$.

The above-mentioned explanation has been made to show the principle of the Fourier zeugmatography.

In the present example, the two-dimensional

inverse Fourier transformation is carried out for a measured signal $S(t_x, t_y)$ in accordance with the above principle, and image data thus obtained is stored in the memory 17. However, the data stored in the memory 17 is not discrete values of $C(I, J)$ (where $I = 0, 1, \ldots, N-1$; $J = 0, 1, \ldots, N-1$) indicating an actual nuclear spin density distribution $C(x, y)$, but discrete values of $C'(I', J')$ (where $I' = 0, 1, \ldots, N-1$; $J' = 0, 1, \ldots, N-1$) indicating the image $C'(x', y')$ which has a distortion due to the non-uniformity of the static magnetic field. For this reason an arithmetic operation for correction is performed for the values $C'(I', J')$, using data with respect to the intensity distribution of the static magnetic field which is previously stored in the memory 18. Thus, data $C(I, J)$ indicating the actual spin density distribution is obtained. The arithmetic operation for correction will be explained below in detail. As is evident from the equations (2), in the case where the intensity of the static magnetic field at a position corresponding to a picture element in the J-th row, the I-th column deviates from a standard value by an amount $E(I, J)$, the actual spin density $C(I, J)$ at this position is equal to the signal intensity $C'(\xi, \eta)$ at a point having coordinates ξ and η on the image obtained by the inverse Fourier transformation. The coordinates ξ and η are given by the following equations:

$$\left.\begin{aligned}\xi &= I + \frac{1}{G_x}E(I, J)\\ \eta &= J + \frac{1}{G_y}E(I, J)\end{aligned}\right\} \quad \ldots\ldots \quad (8)$$

It should be noted that in equation (8), G_x indicates the intensity increment of the X-gradient magnetic field per one picture element, and G_y the intensity increment of the y-gradient magnetic field per one picture element.

The point having the coordinates ξ and η does not always coincide with a picture element in the J'-th row, the I'-th column (where I' = 0, 1, ..., or N-1; J = 0, 1, ..., or N-1).

In the present example, the deviation E(I, J) of the intensity of the static magnetic field from a standard value is measured at each of the positions corresponding to the picture elements, and the coordinates ξ and η are determined by the equations (8). Then, numeral values i, j, Δ_1, and Δ_2 are determined as follows:

$$i = [\xi],\ j = [\eta],\ \Delta_1 = \xi - i, \text{ and } \Delta_2 = \eta - j \quad \ldots\ldots \quad (9)$$

These values thus determined are previously stored in the memory 18. Incidentally, the sign [ ] indicates the greatest integers which do not exceed a value written in the sign [ ].

Then, for each of the positions, the following equation is calculated by the computer 9:

$$g = (1-\Delta_1)(1-\Delta_2)C'(i, j) + (1-\Delta_1)\Delta_2 C'(i, j+1) + \Delta_1(1-\Delta_2)C'(i+1, j) + \Delta_1\Delta_2 C'(i+1, j+1) \quad \ldots \quad (10)$$

The value $\underline{g}$ thus obtained is displayed as the nuclear spin density C(I, J) at the position corresponding to the picture element in the J-th row, the I-th column. That is,

$$C(I, J) = g \quad \ldots\ldots \quad (11)$$

In other words, the spin density C(I, J) is determined, by interpolation, from data at four points existing around the point (ξ, η).

In more detail, the values $\underline{i}$, $\underline{j}$, Δ_1, and Δ_2 with respect to the position corresponding to the picture element in the J-th row, the I-th column are fetched from the memory 18 into the computer 9, to calculate values $(i + 1)$, $(j + 1)$, $(1 - \Delta_1)$, and $(1 - \Delta_2)$. Then, data $C'(i, j)$, $C'(i + 1, j)$, $C'(i, j + 1)$, and $C'(i+1, j+1)$ are fetched from the memory 17, to calculate the equation (10). The result of the calculation is used as corrected image data for the picture element in the J-th row, the I-th column. The above processing is performed for all of the picture elements, and the results of such processing are displayed on the CRT display 16. In the image C(I, j) thus obtained, the distortion due to the non-uniformity of the static magnetic field will be removed, if an error caused by interpolation can be neglected.

In the above example, the values $\underline{i}$, j, Δ_1 and Δ_2

stored in the memory 18 can be previously calculated by an external, large-sized computer. However, in the case where the computer 9 has sufficient processing capability. the above calculation can be performed by the computer 9. In this case, the data E(I, J) (where I = 0, 1, ..., N-1; J = 0, 1, ..., N-1) with respect to the static magnetic field is stored in the memory 18. In order to determine the spin density C(I, J), the data E(I, J) at the position corresponding to the picture element in the J-th row, the I-th column is first fetched from the memory 18, and the coordinates ξ and η are calculated from the equations (8). Then, the values $\underline{i}$, $\underline{j}$, Δ_1, and Δ_2 are determined from the equations (9).

Next, explanation will be made on another example of the correction according to the present invention, that is, the case where the distortion of an image caused by both the non-uniformity of a static magnetic field and the non-linearity of gradient magnetic fields is corrected. This correction also can be carried out by the embodiment shown in Fig. 1.

First, the principle of correction in the present example will be explained. In the case where the intensity of a gradient magnetic field varies non-linearly, the intensity of the x-gradient magnetic field and that of the y-gradient magnetic field can be expressed by

$$G_x\{x + h_1(x, y)\} \text{ and } G_y\{y + h_2(x, y)\} \quad \ldots\ldots \quad (12)$$

where $h_1(x, y)$ indicates the deviation of the intensity of the x-gradient magnetic field from a linearly-varying intensity, and $h_2(x, y)$ the deviation of the intensity of the y-gradient magnetic field from a linearly-varying intensity. In the present example, the two-dimensional signal $S(t_x, t_y)$ is given by the following equation:

$$S(t_x, t_y) = \int C(x, y)\exp[-2\pi j\gamma\{(E(x, y) + G_x(x+h_1(x, y)) + (E(x, y) + G_y(y + h_2(x, y))t_y\}]\,dxdy \quad \ldots (13)$$

The above equation (13) can be converted into the equation (3) by using integral variables x' and y' which are given by the following equations:

$$\left.\begin{aligned} x' &= x + \frac{1}{G_x} E(x, y) + h_1(x, y) \\ y' &= y + \frac{1}{G_t} E(x, y) + h_2(x, y) \end{aligned}\right\} \quad \ldots\ldots \quad (14)$$

Accordingly, in the present example, the following equations (18) are used in place of the equations (8):

$$\left.\begin{aligned} \xi' &= I + \frac{1}{G_x} E(I, J) + h_1(I, J) \\ \eta' &= J + \frac{1}{G_y} E(I, J) + h_2(I, J) \end{aligned}\right\} \quad \ldots\ldots \quad (15)$$

That is, the deviation $E(I, J)$ with respect to the static magnetic field and the deviation $h_1(I, J)$ and $h_2(I, J)$ with respect to the gradient magnetic fields should be measured at each of positions corresponding to picture

elements. Note that in equation (15), G_x and G_y are the increments per one picture element. The coordinates ξ' and η' are calculated from the equations (15), using the measured values of E(I, J), $h_1(I, J)$, and $h_2(I, J)$. Then, values i, j, Δ_1, and Δ_2 for each position are determined as follows:

$$\left.\begin{array}{l} i = [\xi'],\ j = [\eta'] \\ \Delta_1 = \xi' - i,\ \Delta_2 = \eta' - j \end{array}\right\} \quad \cdots\cdots \quad (16)$$

These data i, j, Δ_1, and Δ_2 are previously stored in the memory 18. Then, the spin density C(I, J) at each position is calculated from the equation (10) (that is, by interpolation), using uncorrected image data C(i, j), C(i, j+1), C(i+1, j), and C(i+1, j+1) stored in the memory 17 and data i, j, Δ_1, and Δ_2 stored in the memory 18. When the spin density C(I, J) thus obtained is displayed on the CRT display 16, an image can be obtained in which the distortion due to both the non-uniformity of the static magnetic field and the non-linearity of the gradient magnetic fields has been corrected.

In the present example, the data i, j, Δ_1, and Δ_2 are stored in the memory 18. However, the data E(I, J) with respect to the static magnetic field and the data $h_1(I, J)$ and $h_2(I, J)$ with respect to the gradient magnetic fields may be stored, instead of the data i, j, Δ_1, and Δ_2. In such a modified version of the present example, the computer 9 is required to perform arithmetic operations

given by the equations (15) and (16), prior to the calculation for interpolation.

In the above description, the present invention has been explained for the case where the two-dimensional Fourier zeugmatography is used. However, the present invention is not limited to the two-dimensional Fourier zeugmatography, but is applicable to the spin warp imaging in a manner as mentioned below. (As mentioned previously, the spin warp imaging is another one of the direct Fourier imaging methods in which the values of the nuclear spin density distribution in a to-be-inspected body are measured at points on a rectangular coordinate system in the Fourier space.)

Fig. 3 shows an operation for deriving the image of a cross section by the two-dimensional spin warp imaging, and corresponds to Fig. 2 which shows an operation according to two-dimensional Fourier zuegmatography. In Fig. 3, the same reference symbols as in Fig. 2 are used in the same sense as in Fig. 2.

The spin warp imaging shown in Fig. 3 is different in the operation at a second period 2 from the Fourier zeugmatography shown in Fig. 2. That is, in the Fourier zeugmatography, the period t_y when the y-gradient magnetic field is applied, is set to have various values in the second period 2, and measurement the NMR signal is measured for each value of the period t_y. While, in the spin warp imaging, the period t_y is fixed (that is, the y-gradient magnetic field is applied for a fixed period t_0),

but the amplitud of gradient G_y is set to have various values. That is, the measurement of NMR signal is performed for each value of G_y. A two-dimensional signal $S(G_y, t_x)$ thus obtained is related to the actual spin density distribution $C(x, y)$, as mentioned below:

$$S(G_y, t_x) = \int C(x, y)\exp[-2\pi j\gamma\{(E(x,y) + G_x(x+h_1(x, y))t_x + E(x, y)t_c + G_y(y+h_2(x, y))t_0\}]dxdy \quad \ldots \; (17)$$

It is to be noted that a relaxation term is neglected in the equation (17) and the intensity of the y-gradient magnetic field is expressed by $G_y(y + h_2(x, y))$. Incidentally, reference symbol t_c in Fig. 3 indicates a time interval between a time when a 90° RF pulse is applied and a time when the observation of spin echo is started. The equation (17) can be changed to the following equation:

$$S(G_y, t_x) = \int C(x, y)e^{-2\pi j\gamma E(x,y)t_c} \exp[-2\pi j\gamma\{E(x, y) + G_x h_1(x, y) + G_x x)t_x + G_y t_0(y + h_0(x, y)\}]dxdy \quad \ldots \; (18)$$

Now, let us perform the following transformation of coordinate system:

$$\left.\begin{aligned} x' &= x + \frac{1}{G_x}E(x, y) + h_1(x, y) \\ y' &= y + h_2(x, y) \end{aligned}\right\} \quad \ldots\ldots \quad (19)$$

Then, the equation (19) is changed to the following equation:

$$S(G_y, t_x) = \int C'(x', y') \exp[-2\pi j\gamma(G_x x' t_x + G_y y' t_0)] dxdy \quad \ldots\ldots \quad (20)$$

From the equations (19), the coordinates x and y can be expressed as follows:

$$\left. \begin{aligned} x &= g_1(x', y') \\ y &= g_2(x', y') \end{aligned} \right\} \quad \ldots\ldots \quad (21)$$

By using the equations (21), the image data C'(X', Y') is given by the following equation:

$$C'(x', y') = C'(g_1(x', y'), g_2(x', y')) e^{-2\pi j\gamma E(g_1(x', y'), g_2(x', y')) t_c} \quad \ldots\ldots \quad (22)$$

Thus, the absolute value of the image data is given as follows:

$$|C'(x', y')| = |C(g_1(x', y'), g_2(x', y'))| \quad \ldots\ldots \quad (23)$$

The equation (23) shows that the absolute value of the image data is distorted by the non-uniform intensity distribution of a static magnetic field and the non-linear intensity distribution of gradient magnetic fields. Such a distortion can be corrected in the same manner as in

the previously-mentioned Fourier zeugmatography, except that the following equations (24) are used in place of the equations (8).

$$\left.\begin{aligned} \xi &= I + \frac{1}{G_x}E(I, J) + h_1(I, J) \\ \eta &= J + h_2(I, J) \end{aligned}\right\} \quad \cdots\cdots \quad (24)$$

where G_x indicates the intensity increment of the x-gradient magnetic field per one picture element, as in the equations (8) and (15).

The above-mentioned processing for the correction is performed by the embodiment shown in Fig. 1, in accordance with the following procedure. The error $E(I, J)$ in a static magnetic field and errors $h_1(I, J)$ and $h_2(I, J)$ in gradient magnetic fields are measured at each of the positions corresponding to picture elements, and then the coordinates ξ and η are calculated from the equations (24). The values (i, j) and (Δ_1, Δ_2) are determined by the equations (9), and stored in the memory 18. The computer 9 performs the arithmetic operation for interpolation given by the equation (10), for each of the positions corresponding to the picture elements, using the data stored in the memory 18 and uncorrected image data $C'(I', J')$ stored in the memory 17. The results of the above arithmetic operation are displayed, as the image data $C(I, J)$, on the CRT display 16.

Further, in this case, measured data $E(I, J)$,

$h_1(I, J)$, and $h_2(I, J)$ indicating errors in the magnetic fields may be stored in the memory 18, provided that the computer 9 performs the arithmetic operations given by the equations (24) and (9), prior to the arithmetic operation for interpolation.

As can be seen from the equations (19) and (20), according to the spin warp imaging, the non-uniformity of the static magnetic field causes a distortion only in the x-direction of the image, and does not cause any distortion in the y-direction, if the deviation of the intensity distribution of each gradient magnetic field from a linear intensity distribution is negligibly small. In this case, only the values ξ, $\underline{i}$, and Δ_i are determined by the following equations:

$$\xi = I + \frac{1}{G_x}E(I, J) \quad \ldots\ldots\ldots\ldots\ldots \quad (25)$$

$$i = [\xi] \quad \ldots\ldots\ldots\ldots\ldots \quad (26)$$

$$\Delta_1 = \xi - i \quad \ldots\ldots\ldots\ldots\ldots \quad (27)$$

Further, in order to correct the distortion of the image, the computer 9 performs the following arithmetic operation for interpolation between two points:

$$C(I, J) = (1 - \Delta_1)C'(i, J) + \Delta_1 C'(i + 1, J) \quad \ldots\ldots \quad (28)$$

In the foregoing description, explanation has been made using the original sequences which have

been devised by the proposers of each of the Fourier zeugmatography and the spin warp imaging. However, in addition to the original sequences, various modified sequences are now used which are improved versions of the original sequences. Now, the present invention will be explained for the case where the improved sequences are used.

Figs. 4 and 5 show examples of the improved sequences. The main feature of the sequences shown in Figs. 4 and 5 resides in that a spin echo is formed by using a 180° pulse.

The operation at each of first, second, third, and fourth periods (1), (2), (3), and (4) shown in Fig. 4 will be explained below, by way of example.

At the first period (1), a 90° RF pulse according to the selective irradiation method is emitted while applying the z-gradient magnetic field to the to-be-inspected body, so that the nuclear spin in a specified cross section parallel to the x-y plane is inclined by an angle of 90°. For details of the RF pulse according to the selective irradiation method, an article entitled "Medical Imaging by NMR" (British J. of Radiography, Vol. 50, 1977, pages 188 to 194) should be referred to.

At the second period (2), a 180° RF pulse according to the selective irradiation method is emitted when a time τ has elapsed after the 90° RF pulse was emitted, and thus the nuclear spin in the cross section which is selected at the first period (1), is reversed in

orientation, to observe an echo signal when a time 2τ has elapsed after the 90° RF pulse was emitted.

At the third period (3), the y-gradient magnetic field is applied for a time t_y.

At the fourth period (4), the x-gradient magnetic field is applied and the measurement of the echo signal is started, immediately after the y-gradient magnetic field is removed.

The time t_y (that is, a period when the y-gradient magnetic field is applied) is set to various values, and the above measurement is made for each of such values. A two-dimensional signal $S(t_x, t_y)$ thus obtained is given as follows:

$$S(t_x, t_y) = \int C(x, y)\exp[2\pi j\gamma\{G_y y t_y + (E(x, y) + G_x x)t_x\}]dxdy \quad \text{....} \quad (29)$$

In deriving equation (29), it is assumed that field gradient non-linearities are negligible. It is to be noted that the non-uniformity of the static magnetic field has no effect on the image in the y-direction, as in the spin warp imaging shown in Fig. 3. This is because an echo is formed by using the 180° RF pulse.

The sequence shown in Fig. 5 is different from that shown in Fig. 4 in that the y-gradient magnetic field is applied for a fixed time t_0, and the amplitude thereof is set to various values. Accordingly, in this

case, a two-dimensional signal $S(t_x, G_y)$ is given as follows:

$$S(t_x, G_y) =$$
$$\int C(x, y)\exp[-2\pi j\gamma\{G_y y t_0 + (E(x, y) + G_x x)t_x\}]dxdy \quad \text{.... (30)}$$

Thus, the non-uniformity of the static magnetic field produces no effect on the image in the y-direction. Accordingly, in the case where either one of the sequences shown in Figs. 4 and 5 is used, the distortion of the image can be corrected in the same manner as the absolute value of the image data which is obtained by using the sequence shown in Fig. 3, is corrected. That is, in the case where it is required to correct the distortion caused only by the non-uniformity of the static magnetic field, the coordinate ξ is calculated from the equation (25), and correction is made by the equation (28). Further, in the case where it is required to correct the distortion caused by both the non-uniformity of the static magnetic field and the non-linearity of the gradient magnetic fields, the coordinates ξ and η are calculated from the equations (24), and correction is made by the equation (10).

In various examples mentioned above, the deviation $E(I, J)$ of the intensity of the static magnetic field from a standard value and the deviation $h_1(I, J)$ and $h_2(I, J)$ of respective intensities of the gradient magnetic fields from linearly-varying intensities are

measured at each of the positions corresponding to picture elements, and data necessary for correcting the distortion of the image are calculated from the measured values, to be stored in the memory 18. However, it takes a lot of time to obtain the measured values. Accordingly, the deviation with respect the static magnetic field and the deviation with respect to the gradient magnetic field may be measured at intervals of several positions, to determine deviation values at the positions where measurement is not made, by interpolation. Further, in the case where the intensity distribution of the static magnetic field and that of each gradient magnetic field can be approximated with some functions, the values of the deviation E(I, J), h_1(I, J), and h_2(I, J) used in the above-mentioned examples may be calculated from such functions.

In the foregoing description, various examples of the correction according to the present invention have been explained on the assumption that the formulae (5) hold. However, in the case where the intensity distribution of the static magnetic field is extremely non-uniform, the formulae (5) do not hold, and therefore the denominator on the right-hand side of the equation (4) has to be corrected.

Now, the processing in such a case will be explained below.

When the denominator on the right-hand side of the equation (4) is expressed by W, the denominator W is given as follows:

$$W = 1 + \frac{1}{G_y}\frac{\partial E(x, y)}{\partial y} + \frac{1}{G_x}\frac{\partial E(x, y)}{\partial x} \quad \ldots\ldots \quad (31)$$

By using discrete variables I and J in place of the continuous variables $\underline{x}$ and $\underline{y}$, the equation (31) is changed to the following equation:

$$W = 1 + \frac{1}{G_y}\{E(I, J+1) - E(I, J)\} + \frac{1}{G_x}\{E(I+1, J) - E(I, J)\} \quad \ldots\ldots \quad (32)$$

where G_x indicates the field gradient increment per one picture element in the x-direction, and G_y the field gradient increment per one picture element in the y-direction. As mentioned previously, the value of E(I, J) can be determined by measurement.

In order to obtain corrected image data C(I, J) for a picture element in the J-th row, the I-th column, the values $\underline{i}$, $\underline{j}$, Δ_1, and Δ_2 are determined from the equations (9) on the basis of the equations (8) (for the Fourier zeugmatography) or the equations (24) (for the spin warp imaging), and then the value of $\underline{g}$ is calculated from the equation (10). Next, the value of W is calculated from the equation (32), to determine the corrected image data C(I, J) as follows:

$$C(I, J) = gW \quad \ldots\ldots \quad (33)$$

Thus, even in the case where the intensity distribution of the static magnetic field is extremely non-uniform so that the formulae (5) do not hold, the distortion of the image caused by the non-uniformity of the static magnetic field can be corrected.

Now, a method of measuring the intensity distribution of a magnetic field in a field of view will be additionally explained. The present invention deals with the non-linearity of a static magnetic field and the non-linearity of a gradient magnetic field which correspond to about 0.001 percent of the intensity of the static magnetic field. Such high-accuracy measurement c cannot be made by a conventional magnetic field measuring instrument (since the measuring accuracy of, for example, a gaussmeter is about 0.1 percent of the intensity of a static magnetic field), but can be carried out by a method which utilizes the NMR phenomenon in the following manner. That is, the frequency of the resonance signal is measured at various positions in a field of view by moving a probe which is formed by winding a signal detecting coil round a tube having a diameter of about 1 mm and filled with a substance to be imaged (for example, water). The frequency $\underline{f}$ of the resonance signal is proportional to the intensity H of the magnetic field, and the proportional constant is equal to a gyromagnetic ratio. Accordingly, the value of the magnetic field intensity H at a position can be determined very accurately from the frequency $\underline{f}$ of the resonance signal obtained at this position.

CLAIMS:

1. An imaging apparatus using the nuclear magnetic resonance and provided with means (1, 10) for forming a static magnetic field in a predetermined field of view, means (4x, 4z, 5, 6, 7, 8) for forming a gradient magnetic field in said field of view, means (3, 12, 13) for forming a high-frequency magnetic field in said field of view, signal detecting means (3, 14, 15) for detecting a nuclear magnetic resonance signal from a to-be-inspected body (2) placed in said field of view, and a computer (9) for performing an arithmetic operation for the detected signal to obtain the nuclear magnetic resonance signal intensity distribution in said field of view from measured values of said nuclear magnetic resonance signal intensity distribution at various points on a rectangular coordinate system in the Fourier space, said imaging apparatus comprising:

a first memory (17) for storing therein first image data, said first image data being obtained, by calculation, from the output of said signal detecting means, said first image data indicating said nuclear magnetic resonance signal intensity distribution in said to-be-inspected body on the basis of a measuring co-ordinate system; and

a second memory (18) for storing therein data with respect to the magnetic field intensity distribution in said field of view, to correct the coordinate of said first image data stored in said first memory on the basis

of said data stored in said second memory, thereby producing second image data, said second image data being displayed on a display device (16).

2. An imaging apparatus using the nuclear magnetic resonance according to Claim 1, wherein said second memory stores therein data indicating the spatial distribution of the deviation of the intensity of said static magnetic field from a predetermined value.

3. An imaging apparatus using the nuclear magnetic resonance according to Claim 1, wherein said second memory stores therein data indicating the spatial distribution of the deviation of the intensity of said static magnetic field from a predetermined value and data indicating the spatial distribution of the deviation of the intensity of said gradient magnetic field from a predetermined, linearly-varying intensity.

4. An imaging apparatus using the nuclear magnetic resonance according to Claim 1, wherein said second memory stores therein data previously calculated from measured values with respect to the intensity distribution of said static magnetic field and/or the intensity distribution of said gradient magnetic field for converting said first image data $C'(I', J')$ into said second image data $C(I, J)$ through the transformation of coordinate system.

5. An imaging apparatus using the nuclear magnetic resonance according to Claim 4, wherein coordinates ξ and η of said first image data corresponding to coordinates I and J on a to-be-displayed image (where $I = 0, 1, \ldots, N-1$;

$J = 0, 1, \ldots, N-1$) are divided into discrete coordinate components $\underline{i}$ and $\underline{j}$ and error components Δ_1 and Δ_2 as indicated by equations $\Delta_1 = \xi - i$ and $\Delta_2 = \eta - j$, and said second memory stores therein said discrete coordinate components $\underline{i}$ and $\underline{j}$ and said error components Δ_1 and Δ_2.

6. An imaging apparatus using the nuclear magnetic resonance according to Claim 5, wherein said coordinates ξ and η are corrected by said components $\underline{i}$, $\underline{j}$, Δ_1, and Δ_2 in such a manner that said second image data is obtained by interpolation from said first image data at four positions having coordinates $\underline{i}$ and $\underline{j}$, coordinates $\underline{i}$ and $j+1$, coordinates $i+1$ and $\underline{j}$, and coordinates $i+1$ and $j+1$.

7. An imaging apparatus using the nuclear magnetic resonance according to Claim 5, wherein said coordinates ξ and η are calculated substantially from the following equations:

$$\xi = I + \frac{1}{G_x} E(I, J)$$

$$\eta = J + \frac{1}{G_y} E(I, J)$$

where G_x indicates an intensity increment of a gradient magnetic field having an intensity gradient in an x-direction per one picture element, G_y an intensity increment of a gradient magnetic field having an intensity gradient in a y-direction per one picture element, and $E(I, J)$ the deviation of the intensity of said static magnetic field from a predetermined value at a position having coordinates I and J.

8. An imaging apparatus using the nuclear magnetic resonance according to Claim 5, wherein said coordinates ξ and η are calculated substantially from the following equations:

$$\xi = I + \frac{1}{G_x}\{E(I, J) + h_1(I, J)\}$$

$$\eta = J + \frac{1}{G_y}\{E(I, J) + h_2(I, J)\}$$

where G_x indicates an intensity increment of a gradient magnetic field having an intensity gradient in an x-direction per one picture element, G_y an intensity increment of a gradient magnetic field having an intensity gradient in a y-direction per one picture element, $E(I, J)$ the deviation of the intensity of said static magnetic field from a predetermined value at a position having coordinates I and J, $h_1(I, J)$ the deviation of the intensity of said gradient magnetic field having an intensity gradient in the x-direction from a predetermined, linearly-varying intensity at said position having the coordinates I and J, and $h_2(I, J)$ the deviation of the intensity of said gradient magnetic field having an intensity gradient in the y-direction from a predetermined, linearly-varying intensity at said position having the coordinates I and J.

9. An imaging apparatus using the nuclear magnetic resonance according to Claim 5, wherein a 180° high-frequency pulse is applied to said to-be-inspected body to detect said nuclear magnetic resonance signal, and said coordinates ξ and η are calculated from the following equations:

$$\xi = I + \frac{1}{G_x}\{E(I, J) + h_1(I, J)\}$$

$$\eta = J + h_2(I, J)$$

where x is taken in the direction of the gradient of a gradient magnetic field applied for measuring a nuclear magnetic resonance signal, G_x indicates an intensity increment of a gradient magnetic field having an intensity gradient in an x-direction per one picture element, E(I, J) the deviation of the intensity of said static magnetic field from a predetermined value at a position having co-ordinates I and J, $h_1(I, J)$ the deviation of the intensity of said gradient magnetic field having an intensity gradient in the x-direction from a predetermined, linearly-varying intensity at said position having the coordinates I and J, and $h_2(I, J)$ the deviation of the intensity of a gradient magnetic field having an intensity gradient in a y-direction from a predetermined, linearly-varying intensity at said position having the coordinates I and J.

10. An imaging apparatus using the nuclear magnetic resonance according to Claim 1, wherein said second image data is an image signal whose intensity has been corrected by data stored in said first memory.

11. An imaging apparatus using the nuclear magnetic resonance according to Claim 4, wherein a 180° high-frequency pulse is applied to said to-be-inspected body to detect said nuclear magnetic resonance signal, and wherein one coordinate ξ of coordinates ξ and η of said first image

data corresponding to coordinates I and J on a to-be-displayed image is divided into a discrete coordinate component i and an error component Δ_1 as indicated by an equation $\Delta_1 = \xi - i$, and said second memory stores therein said coordinate component i and said error component Δ_1.

12. An imaging apparatus using the nuclear magnetic resonance according to Claim 11, wherein said coordinate ξ is corrected by said components i and Δ_1 in such a manner that said second image data is obtained by interpolation from said first image data at two positions having coordinates i and J and coordinates $i+1$ and J.

13. An imaging apparatus using the nuclear magnetic resonance according to Claim 11, wherein said coordinate is calculated from the following equation:

$$\xi = I + \frac{1}{G_x} E(I, J)$$

wherein G_x indicates an intensity increment of a gradient magnetic field having an intensity gradient in an x-direction per one picture element, and E(I, J) the deviation of the intensity of said static magnetic field from a predetermined value at a position having coordinates I and J.

14. An imaging method comprising the steps of:

(a) measuring values of a nuclear magnetic resonance signal intensity distribution in a field of view at various points on a rectangular coordinate system in the Fourier

space,

(b) correcting values of coordinates in said measured values in a form of an image data with a data of a magnetic distribution measured in said field of view, and

(c) displaying said corrected values in said form of said image data in a display (16).

FIG. I

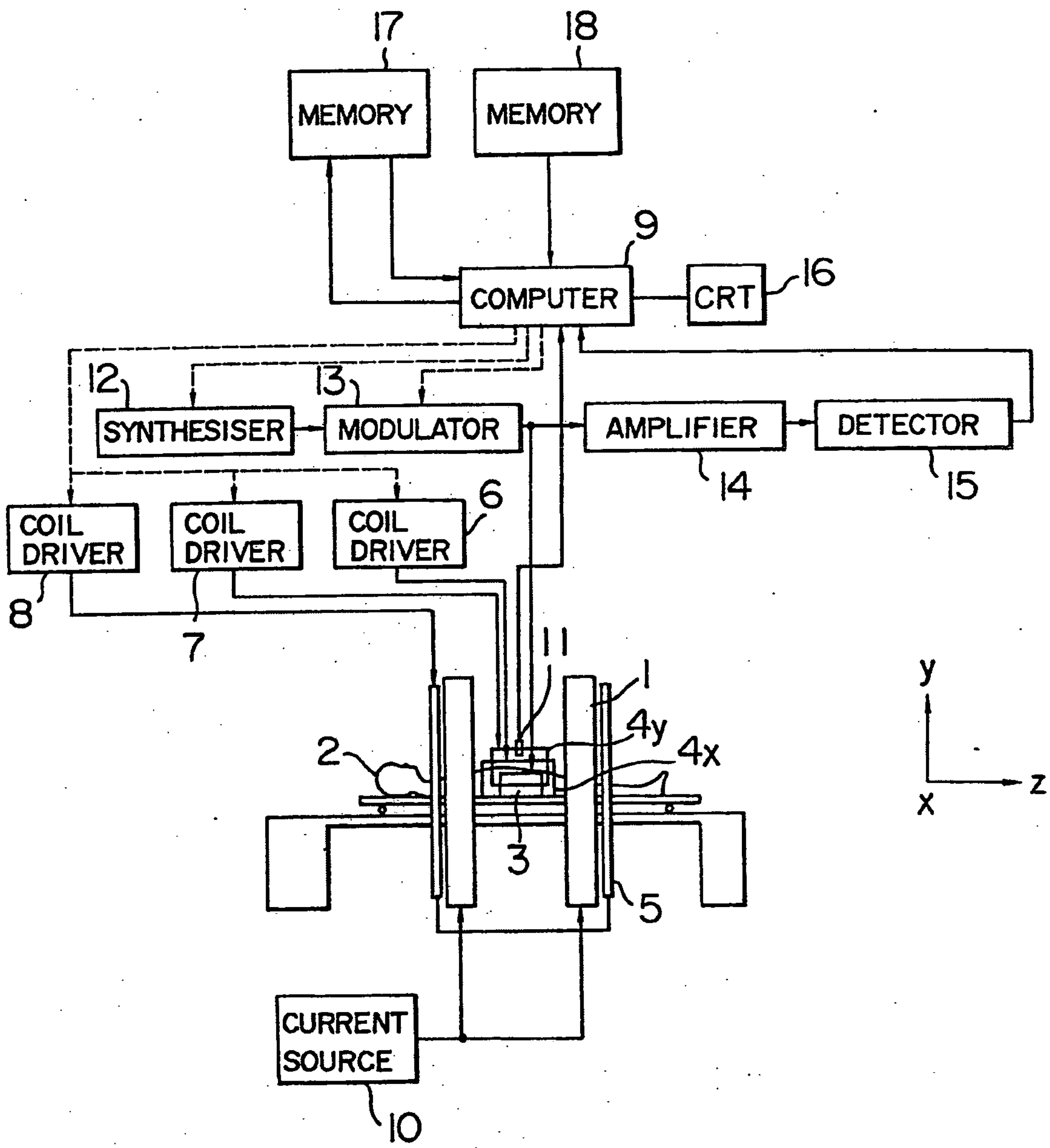
17
18
MEMORY
MEMORY
9
COMPUTER
CRT
16
12
SYNTHESISER
13
MODULATOR
AMPLIFIER
DETECTOR
14
15
COIL DRIVER
COIL DRIVER
COIL DRIVER
6
8
7
11
1
4y
4x
2
3
5
y
z
x
CURRENT SOURCE
10

FIG. 2

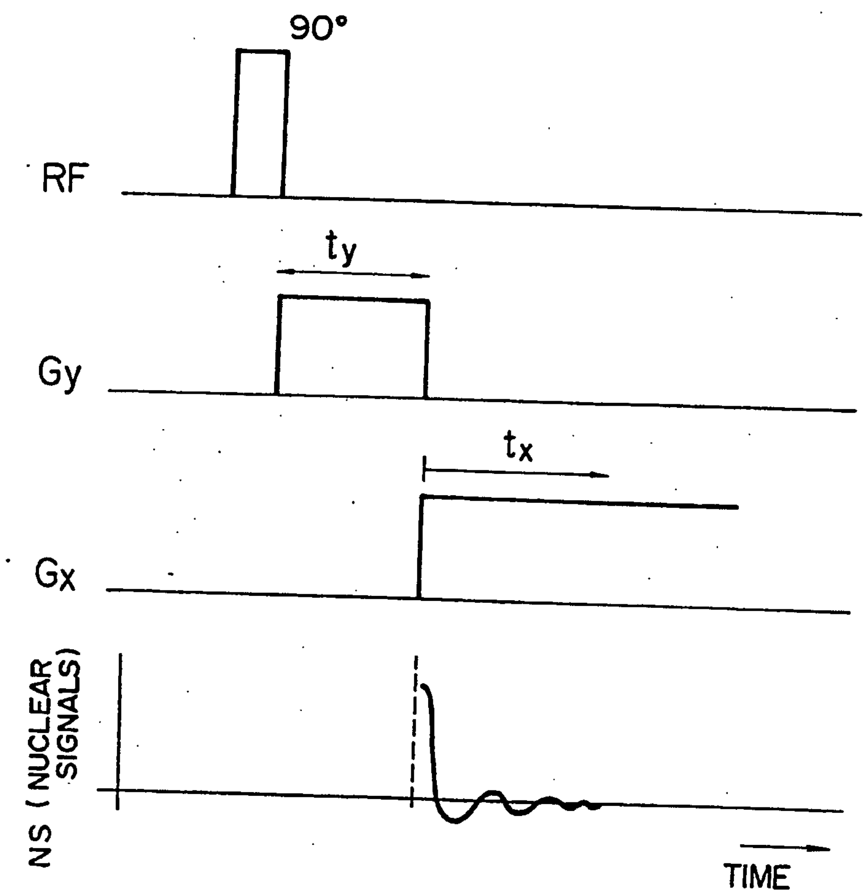

FIG. 3

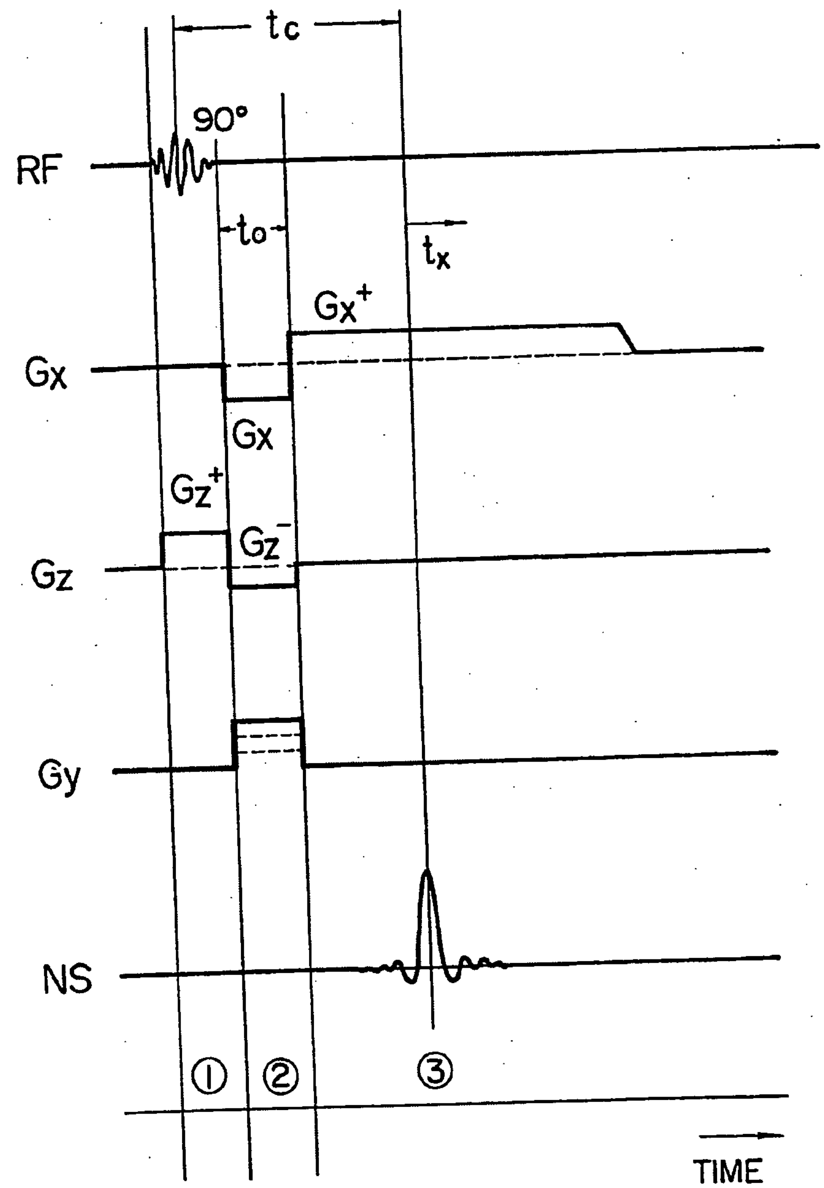

FIG. 4

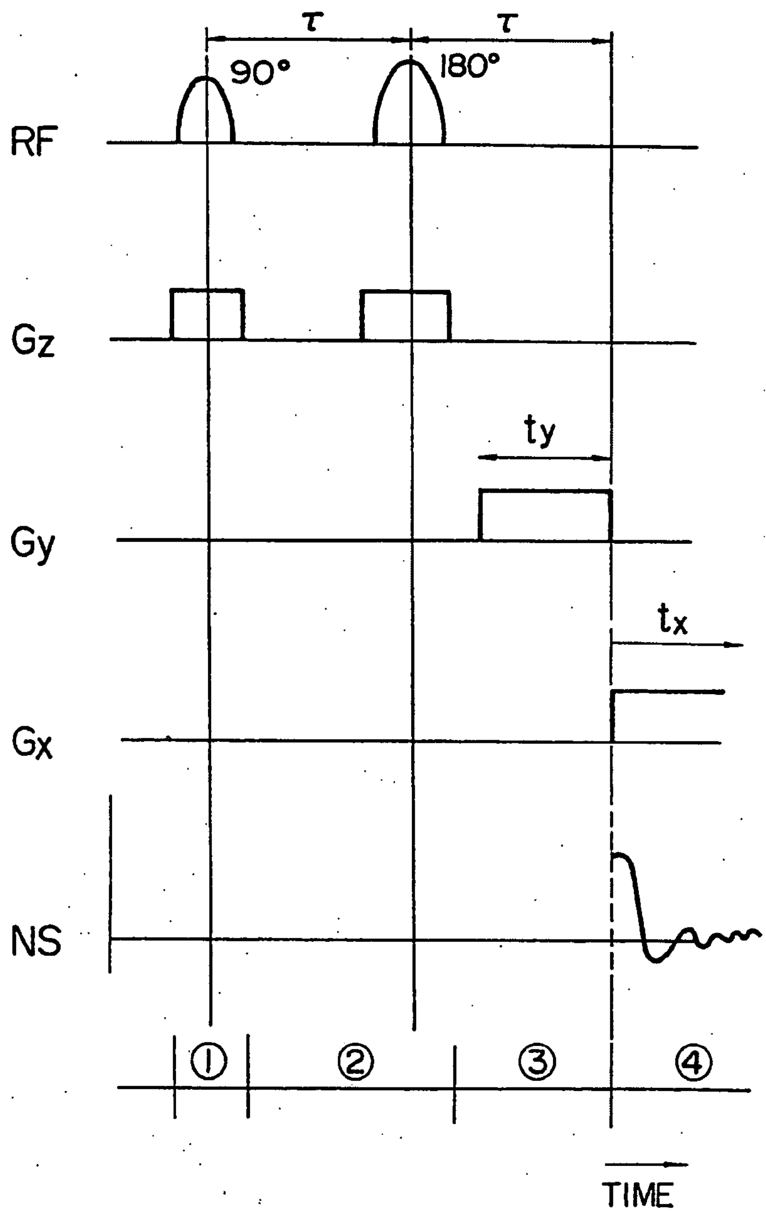

FIG. 5